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***Abstract*—Recently, the application of unmanned aerial vehicles (UAVs) to support the base stations in cellular telecommunication networks attracts attentions. UAV-assisted base stations can provide the extra users' demand in extreme and/ or unpredictable situations such as Olympic Games to avoid extra cost of installing ground base stations. In this paper, a PV-battery power system is presented to supply UAV-assisted base stations in cellular telecommunication networks in urban areas to prevent environmental issues as well as to reduce the cost of fulfilling the energy demand. First, the power consumption profile of the batteries of UAVs is estimated. Afterwards, the impact of the PV system sizing and battery capacity are studied based on sensitivity analysis.**

***Keywords*—PV-battery power system, UAV-based base stations, wireless telecommunication networks**

I. Introduction

To satisfy the wireless users' expectation to have access to unlimited capacity everywhere and all the time, a cost-effective solution should be suggested to substitute the deployment of a very dense network of base stations [1]. On one hand, the deployment of such a dense network is not effective and feasible from CAPEX and OPEX points of view, on the other hand, these base stations may not have any load at a given time and space [2]. Furthermore, the traffic patterns are difficult to be predicted due to the temporal and spatial variations in user densities and application [3]. These challenges led to the consideration of the UAV-aided telecommunication networks as an auspicious solution [1-4].

UAVs can improve wireless telecommunication networks owing to their different features such as high coverage, low cost, high mobility, adjustable height, and flexible installation [1, 2]. A variety of scenarios can be defined for applying UAVs in telecommunication networks including assistant aerial base stations in rural and urban areas as well as aerial user equipment such as surveillance drones and etc. [1, 2].

By providing high data rate coverage, UAV-based base stations can cooperate ground base stations in urban areas in severe situations such as Olympic games and festivals or in unpredictable occasions when the users' demand increases leading to an extreme need in space and time [1-4].

On the other hand, one main concern of deploying UAVs is the limitation of their batteries which require to be charged in recharging sites connected to the electricity grid. This in turn leads to an increase in cost and demand of electricity [5]. A promising solution to manage this challenge is the application of renewable energy sources (RESs), such as photovoltaic (PV) panels to support main electricity grid in high demand hours [5, 6]. RESs can improve the satisfaction of energy demand and reduction of the fossil pollutants on the environment [5, 6].

Different approaches for solving the problem of energy management of renewable-based base stations were studied in [7-9]. In [7], battery aging method was proposed to calculate the optimum sizing of the PV-battery system. In order to determine the size of the PV-battery system of a renewable-based base station, authors suggested a power outage probability assessment in [8]. In [9], an analytical model of renewable fluctuation was suggested to decide on the battery size of the power supply system.

In [10-14], different UAV applications in wireless networks were investigated. An energy-efficient mission planning of a UAV-aided PV-battery-powered cellular network was suggested in [10]. The main objective was to minimize the energy consumption of UAVs while providing the cellular coverage. The goal of [11] was to minimize the total costs of a UAV-based 5G network. In [12] the energy consumption of UAVs in a 5G network in rural areas was minimized. The energy consumption management of a drone-based cellular network in low income and rural areas was considered in [13] with the objective of minimizing the stored energy in UAV batteries and charging sites. In [14], based on minimizing the energy purchased from the electricity grid, and maximizing the sold energy to the grid in a drone-based cellular network a compromise between maximizing the throughput and minimizing OPEX was proposed.

In this paper, the impact of PV-battery power supply on the operation of UAV-assisted base station in a cellular network in a specific urban area based on the estimated power consumption profile of UAVs is presented. The impacts of the sizing the PV system and the capacity of the batteries on the extracted electricity from the grid are investigated through sensitivity analysis.

The main contributions of this paper are as follows:

1. Investigating the operation of PV-battery-powered UAV-assisted base stations in cellular telecommunication networks in urban areas.

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2. Estimation the power consumption profile of UAV-assisted base stations in cellular telecommunication networks as a recharging station.
3. Assessing the impact of the PV system sizing and battery capacity based on sensitivity analysis.

II. System Structure

Fig. 1. shows the configuration of a UAV-assisted cellular telecommunication network in which PV-battery system is applied alongside of the main electricity grid.

A. Modelling of the PV-Battery System

In this section, first, the considered model of the generated PV power is presented as follows [5]:

$$P_{PV}^{t}=\frac{I^{t}(\theta,\gamma)\times P_{PV}^{Peak}\times(1+dp(T_{C}^{t}-25))}{1000} \quad (1)$$

$$I^{t}(\theta,\gamma)=I_{b}^{t}(\theta,\gamma)+I_{d}^{t}(\theta,\gamma)+I_{g}^{t}(\gamma) \quad (2)$$

$$T_{C}^{t}=T_{a}^{t}+\left[\frac{NOCT-20}{800}\right]\times I^{t}(\theta,\gamma) \quad (3)$$

where the PV system's rated power is presented by P_{PV}^{t}. $I^{t}(\theta,\gamma)$, $I_{b}^{t}(\theta,\gamma)$, $I_{d}^{t}(\theta,\gamma)$ and $I_{g}^{t}(\gamma)$ are the received solar irradiance by the PV system, the direct-beam, sky-diffuse, and ground-reflected components, respectively. $dp=-0.4\%/℃$ (for crystalline silicon solar cells technology [5]) is the temperature coefficient. T_{C}^{t} and T_{a}^{t} are the cell and ambient temperatures, respectively. the nominal operating cell temperature is $NOCT=45℃$ [5]. t is the number of the time slot. The yearly solar irradiation of the considered case study is taken from [5].

The needed energy for recharging the UAVs' batteries in a charging site is assumed to be provided by PV panels. To satisfy the needed energy of the UAV's battery in cases when the generated power of PV panels is not enough (and/or when no solar energy is available, for example, during nights or in cloudy weather,) then the batteries of the charging sites will provide the power requirement of the UAV's battery [5].

The following are considered for the battery charging/discharging rates and the state of charge (SOC) constraints [5]:

$$SOC_{Batt,min}\le SOC_{Batt}^{t}\le SOC_{Batt,max} \quad (4)$$

$$SOC_{Batt}^{t}=SOC_{Batt}^{t-1}+\frac{\eta_{Ch}P_{Ch}^{t}.\Delta t}{C_{Batt}}+\frac{P_{Dch}^{t}.\Delta t}{\eta_{Dch}.C_{Batt}} \quad (5)$$

$$P_{Ch,min}\le P_{Ch}^{t}\le P_{Ch,max} \quad (6)$$

$$P_{Dch,min}\le P_{Dch}^{t}\le P_{Dch,max} \quad (7)$$

where SOC_{Batt}^{t} is the battery SOC at time *t*, $SOC_{Batt,min}$ and $SOC_{Batt,max}$ are the minimum and maximum SOC of the battery. P_{Ch}^{t} and P_{Dch}^{t} are the battery charge and discharge rates at time *t*, C_{Batt} is the battery capacity, η_{Ch} and η_{Dch} are the battery charge and discharge efficiencies, respectively. $P_{Ch,min}$ and $P_{Ch,max}$ are the battery minimum and maximum charge rates, $P_{Dch,min}$ and $P_{Dch,max}$ are the minimum and maximum battery discharge rates, respectively.

B. Modelling of UAVs' Energy Consumption Profile

To design the PV-battery system of the charging sites optimally, the energy consumption profile of [5] is considered.

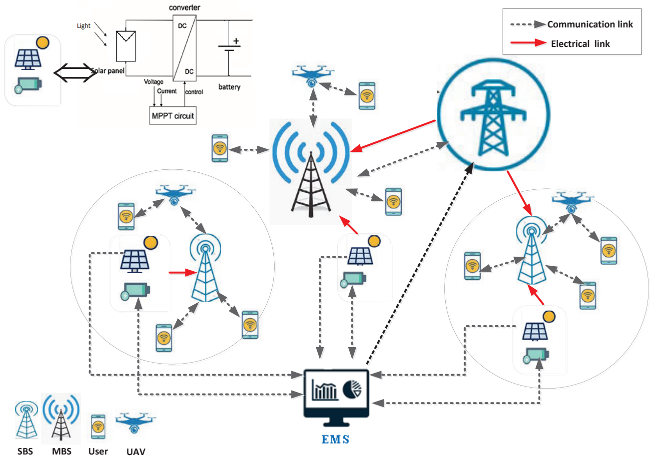

Fig. 1. Configuration of a grid-connected UAV-assisted base stations in cellular telecommunication network powered by PV-battery systems.

The urban area of Milano, Italy is considered where there are eight areas (refers to the locations that should be covered by UAVs) and three ground base stations. The power consumption profile of the base station related to UAVs operation is based on [5]. It is assumed that the UAVs' mission planning is during the first 8 hours of the weekdays (from 8 am to 4 pm). To match with the battery capacity of the UAVs and duration of mission a time slot equal to 10 is considered [5].

III. Simulation Results

To inspect the impact of the UAVs' operation on the power consumption profile of base stations in cellular telecommunication networks and to investigate PV-battery system application as a supplementary sustainable energy supply in green next generation telecommunication networks a PV-battery-powered UAV-assisted base station in Milano, Italy is considered as the case study in this section. The hourly power consumption profiles as in [6] for a base station in commercial urban area on weekdays and weekend are considered.

The same power dispatch strategy as in [6] is considered in this paper. For each time slot that the PV system output power is higher than the load demand, the load is satisfied by the PV and the surplus energy is stored in the battery of the recharging site. If the energy level of the battery equals to the maximum level, the excess energy of the PV-battery system is sold to the electricity grid. If the PV output power is less than load demand in each time slot, the remained required load is satisfied by first discharging the battery. If the stored energy in the battery is not enough to satisfy the load, then the strategy is to buy energy from the electricity grid such that the power equality constraint is fulfilled. This power dispatch strategy leads to less dependency to the electricity grid which in turn results in the increase of the reliability of the system [6].

It is assumed that UAVs assist the ground base station in weekdays and the modeled UAVs energy consumption of Section II is added to the considered load profile of the weekdays. The power consumption profile of the considered cellular telecommunication network with and without UAVs in weekdays and weekends for a base station in different hours of a day is shown in Fig. 2. As is expected, in weekends since the considered scenario is in a urban commercial area, the power consumption level in weekends is less than in weekdays. The observed peaks in Fig. 2. reveals the hours when the UAVs are charging in the recharging sites. The maximum load is equal to 10 kW when there is not any UAV in the network while it equals to 16 kW with UAVs' application.

In Fig. 3. the annual total load when the UAVs are implemented in the system is compared with the case that no UAV is applied in the system. It is observed that the total annual power consumption increases about 1.5 MW. To satisfy this load the green sustainable solutions such as PV systems can be used to decrease the operational cost and to reduce the carbon footprint as well.

In the first scenario, to investigate the PV system (the PV system characteristics are inspired from [6]) impact on the operation of UAV-assisted base stations, it is assumed that only PV system (without battery) is added to the base station as a green power supply. The impact of applying different number of PV panels on the extracted energy from the electricity grid is investigated. It is observed that, with one PV panel with the size of 1.8 m, about 0.7 MW of the annual load is supplied by the PV system, or in other words, 0.7 MW less energy is extracted from the electricity grid. This reduction of energy for number of PV panels 3, 5, 11, 17 and 28 respectively equals to 2, 3.3, 7.2, 10.5 and 15.6 MW according to Fig. 4.

For number of PV panels equal to 17 and 28 which respectively equal 30 and 50 m^2 PV panel, in addition to a reduction of, respectively, 10.5 and 15.6 MW of dependency to the electricity grid, about 0.8 and 3.2 MW power is sold to the electricity grid.

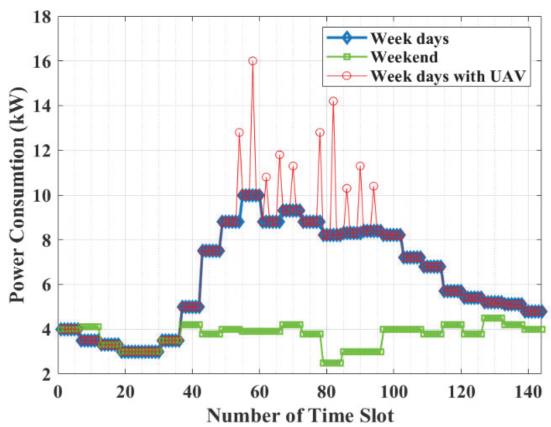

Fig. 2. Power consumption profile of the base stations with/ without UAVs in weekdays and weekends in a commercial urban area.

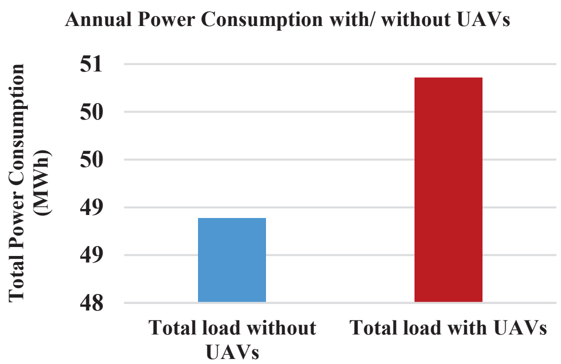

Fig. 3. Total annual power consumption of the base stations with/ without UAVs.

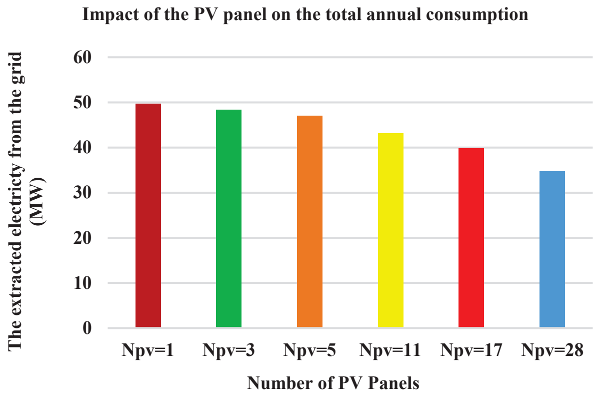

Fig. 4. Impact of the number of PV panels on the extracted energy from the electricity grid in the considered UAV-assisted cllular network.

The second scenario is devoted to the investigation of the impact of the combined PV-battery system on the operation of UAV-assisted base stations. The battery is applicable when the output power of the PV system is more than the demanded load which means that, according to the considered power dispatch strategy, the surplus energy is stored in the battery when the PV output power is more than the demanded load.

According to Fig. 2. the minimum power consumption in a time slot is 3kW. Consequently, the PV-battery system scenario is applicable when the rated power of the PV system is more than 3 kW. Accordingly, in the second scenario, the number of PV panels is considered equal to 28, and the impact of the different battery capacities on the annual extracted electricity from the grid of the considered UAV-assisted base stations in the cellular network is then investigated.

According to Fig. 5. when the battery capacity is 50 kWh, the extracted power from the electricity grid reduces 16.7 MW compared to the case that there is no PV-battery system in the network, while it reduces 1.1 MW compared to the first scenario (when there is only PV system in the network.) This reduction of the extracted power from the electricity grid for the cases of the battery capacity of 5, 10, 20, 30 and 40 kWh is 15.9, 16, 16.3, 16.5 and 16.6 MW, respectively.

One of the most important parameters of battery that directly affects the charging and discharging of the battery is the battery efficiency [15]. Since we considered the battery efficiency equal to 90%, in each charging/ discharging of the battery, the energy loss is about 10 %. Accordingly, we investigated the impact of the battery efficiency on the annual extracted power from the electricity grid when the battery capacity and the number of PV panels equal to 50 kWh and 28, respectively.

In Fig. 6. the impact of battery efficiency on the annual extracted power from the electricity grid is shown. The reduction of the annual extracted power from the electricity grid for the battery efficiencies of 90, 93, 95 and 97 % equals to 16. 7, 16.75, 16.78, 16.8 MW, respectively.

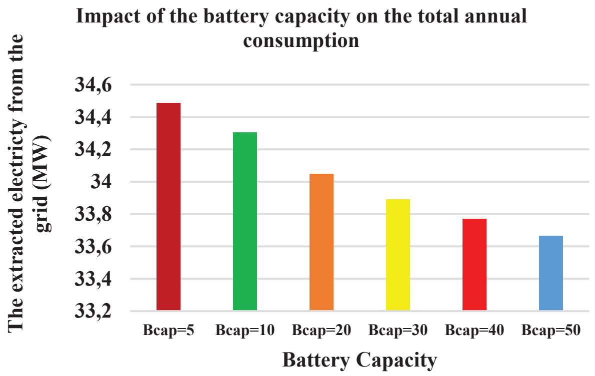

Fig. 5. Impact of the battery capacity on the extracted energy from the electricity grid in the considered UAV-assisted cellular network.

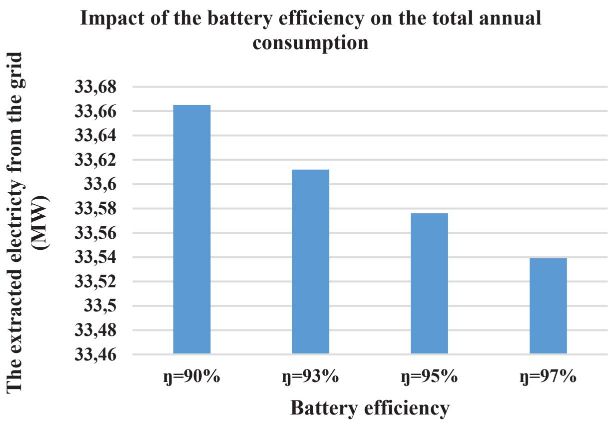

Fig. 6. Impact of the battery efficency on the extracted energy from the electricity grid in the considered UAV-assisted cllular network.

IV. CONCLUSIONS

In next generation telecommunication networks, UAVs can be applied to improve the quality of service and to reduce the latency. While the application of UAVs improves the performance of telecommunication networks, it may lead to the increase of the power consumption, the operational cost of the system as well as the carbon footprint. One sustainable solution for these issues is to apply PV-battery power systems alongside the main electricity grid to supply the energy of the UAV-assisted cellular networks. This approach can reduce both the dependency to the electricity grid and the carbon footprint resulted from the increase of load demand of the telecommunication networks. In this paper, we first investigate the impact of the application of UAVs on the cellular networks and estimate the increase of the load demand. An annual power consumption profile is then generated based on [5, 6]. Afterwards, two different scenarios are considered to inspect the impact of the application of PV-battery systems on the UAV-assisted base stations in cellular networks. In the first scenario, the impact of different number of PV panels in the only PV power supply is investigated. It is observed that for number of PV panels equal to 17 and 28 which respectively equal 30 and 50 m^2 PV panel, in addition to a reduction of, respectively, 10.5 and 15.6 MW of dependency to the electricity grid, about 0.8 and 3.2 MW power is sold to the electricity grid. In the second scenario, the impact of the battery capacity in the combined PV-battery system of the considered UAV-assisted base stations in the cellular network on the annual extracted electricity from the grid is studied. Since the battery efficiency plays an important role on the charging/ discharging of batteries, the impact of different battery efficiencies is also investigated in simulation results. It is observed that the reduction of the annual extracted electricity from the electricity grid is more for the higher battery efficiencies, so with the improvement of the battery technology the operation cost of the PV-battery-powered UAV-assisted base stations decreases.

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